RISK MITIGATION OF LNG SHIP DAMAGE FROM LARGE SPILLS

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ABSTRACT

This paper will summarize LNG ship cryogenic and fire damage and cascading damage potential identified for small to large LNG spills in recent research efforts conducted by Sandia National Laboratories from 2008 through 2011. The level of damage and the cascading damage potential for the different type of LNG ships will be discussed for a range of credible accidental and intentional events. The impact of events have been evaluated for both near-shore and off-shore LNG export and import operations. General and specific risk management approaches that could be considered to reduce the risks and hazards to LNG ships will be presented. Specific cascading damage and risk management concerns, concepts, approaches, and options will be highlighted that have been identified and evaluated by Sandia in cooperation with input from an industrial and regulatory technical peer review panel.

INTRODUCTION

The combination of the potential for the expansion of future imports and exports of liquefied natural gas (LNG) in the U.S., along with the increased safety and security concerns resulting from the incidents of September 11, 2001, have led to an exploration of the impact of an intentional or an accidental breach and spill of an LNG cargo tank would have on the safety of the LNG ship, public safety and property. The US Department of Energy (DOE) has funded several studies (Hightower, et al., 2004, Hightower et al., 2006, Luketa et al., 2008) that have examined the potential hazards from an accidental or intentional breach of an LNG cargo tank and the potential for cascading ship damage, which could lead to larger spills and greater hazards or hazard distances. This paper first summarizes the major results of the detailed LNG ship cryogenic and fire damage and cascading damage studies conducted by Sandia National Laboratories from 2008 through 2011(Kalan et al., 2011, Figueroa et al., 2011, and Petti et al., 2011), to highlight specific ship response and damage concerns raised by the cascading damage testing, modeling, and analysis efforts. Based on these challenges, a series of risk management and mitigation issues, concepts, approaches, and options were identified that could reduce the likelihood or consequences of a major LNG spill. These approaches have been summarized in a DOE Report to Congress on LNG Safety Research (DOE, 2012), and are discussed in detail in this paper.

LNG SHIP DAMAGE AND RISK MITIGATION ANALYSIS OVERVIEW

To study the cascading damage potential, damage progression, and damage prevention or mitigation options possible for an LNG cargo tank breach and spill event, a system-level LNG ship damage and associated hazard evaluation had to first be conducted. The major elements of the LNG Ship Cascading Damage Study are highlighted first in this paper and included:

1 Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy’s National Nuclear Security Administration under Contract DE-AC04-94AL85000.
• A series of high and cryogenic temperature ship structural steel material property testing for use in developing thermal damage models,
• A series of large-scale ship steel cryogenic fracture and damage tests to develop a detailed cryogenic fracture and damage model, and
• Use of high-performance, massively-parallel, computing techniques to model and analyze an LNG cargo tank breach, LNG spill and flow, cryogenic and fire thermal impacts, and assess cascading damage potential of an LNG ship and cargo tanks from an initial spill.

Based on these analyses and the data collected, LNG ship cascading damage potential and overall ship performance, survivability, and stability were estimated. From those results, risk mitigation and management options were evaluated that included structural, design and construction, and operational modifications to consider for reducing the hazards and risks of a potential spill during marine LNG transport. The risk mitigation and management options discussed were developed in cooperation with a technical review panel established by Sandia. The panel consisted of LNG shipping, operations, marine architects, and regulatory agency participants. A summary of their ideas and suggestions are presented in this paper along with clarifying discussions. As always, risk mitigation and management are site-specific, but the options presented provide direction on what LNG experts think should be considered at many ports.

SUMMARY OF LNG SHIP BREACH, SPILL, AND FLOW ANALYSES

Previous DOE directed studies of large LNG spills over water (Hightower et. al., 2004 and Luketa et. al., 2008) have explored potential accidental and intentional damage scenarios. These evaluations have considered a wide range of possible threats including accidents and intentional events. Potential credible events are site-specific, and vary depending on whether the marine transport is in an inner harbor, an outer harbor, or at an offshore Deep Water Port, and the associated hazards depend on the size and design of the LNG ships transporting the LNG and the port environmental conditions.

For both the damage and risk analyses, large ships from both common classes of LNG carriers, Moss and Membrane, were considered. The Membrane LNG ship studied was a large, conformal, 5-tank, Qmax design, which carries ~260,000 m³ of LNG. The ship is similar in design, layout, and construction to the slightly smaller and more common Qflex designs, which carry ~215,000 m³ of LNG, as well as some of the smaller Membrane LNG Ships used in the U.S. The Moss LNG ship studied was a moderately sized, 5-tank Moss spherical design, which carries ~140,000 m³ of LNG. The sizes selected span many of the Moss and Membrane ships used in the U.S. today, including the largest current LNG ships. The general geometric configuration of the Moss and Membrane LNG ships considered and their general cross-sections are shown in Figure 1 and 2, respectively.

Figure 1. Moss LNG Ship Cross-Section
For this study, Sandia focused on evaluating a range of credible breach sizes based on previous credible event studies. The nominal breach sizes selected were based on detailed, two and three dimensional, shock physics/structural damage models. Table 2 summarizes the range of LNG cargo tank breach sizes considered in Sandia’s LNG cascading damage studies. Not all the breach events and breach sizes listed are applicable at all ports, but the breach sizes considered span the range of potential credible events for the types of ports currently or expected to operate in the U.S. The larger holes (5m² to 15m²) represent major intentional events, while the smaller hole sizes represent accidental, operational, or smaller intentional events and spills. To estimate the size of the spills from the identified breach events, the holes identified were evaluated in the most likely and appropriate locations on the ships (e.g., waterline, above waterline, mid-ship, processing areas, etc) that provide the largest spills of LNG. While this makes the analysis somewhat conservative, we tried to make the analysis realistic for likely LNG transport operations with the larger LNG ships.

Table 1. LNG Cargo Tank Breach Sizes Considered

<table>
<thead>
<tr>
<th>Type</th>
<th>Breach Area</th>
<th>Breach Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>0.005 m²</td>
<td>(0.25 feet square)</td>
</tr>
<tr>
<td>Medium</td>
<td>0.5 m²</td>
<td>(2.3 feet square)</td>
</tr>
<tr>
<td>Large</td>
<td>3 m²</td>
<td>(5.7 feet square)</td>
</tr>
<tr>
<td></td>
<td>5 m²</td>
<td>(7.3 feet square)</td>
</tr>
<tr>
<td>Very Large</td>
<td>15 m²</td>
<td>(12.7 feet square)</td>
</tr>
</tbody>
</table>

In order to determine the extent of LNG flow during a spill, three-dimensional computational fluid dynamics (CFD) analyses of the internal and external flow of LNG in the Moss and Membrane cargo tanks were performed. The flow analyses used breach dimensions noted above and assumed they extended through the outer and inner hulls of each ship and into an LNG cargo tank. The CFD analyses included the entire flow physics including the draining of the affected cargo tank, the flow and timing of the LNG flow internal to the ship, the LNG vaporization and migration during spills, and the amount of LNG that would spill outside the ships in order to estimate the size of the LNG pools that would be created on the water.

The CFD flow analyses showed substantial LNG flow inside and outside each ship for the larger breach scenarios. In the case of Moss ships, the design is such that LNG can pool underneath the cargo tank as shown in Figure 3. The LNG flow also extends from the cargo tank region to the double hull (e.g., ballast tank) compartments directly across from the cargo tank hole. Within approximately 30 seconds, widespread flooding occurs in the initial double hull compartments as well as initial flooding of the lower compartments through holes in the steel plating in the ballast tank region. In addition, the LNG has also begun to flow out to the water external to the vessel, forming an external LNG pool (Figueroa et al., 2011).
Similar results were obtained for the other hole sizes for the Moss ship designs. While the general trends identified were similar, the timing and distribution of LNG flow onto the water surface and inside the LNG ship varied, which impact the general timing of ship cryogenic damage and pool fire sizes and hazard distances.

For the large breach events for the Membrane ships, less internal LNG flow was calculated since the Membrane cargo tank is integral with the inner hull. Therefore, a breach in a cargo tank flows directly into the double hull compartments (e.g., ballast tank) and directly outside on to the water. The internal structure of Membrane ships is essentially symmetrical longitudinally along the keel with no penetrations or flow paths across the ship centerline. Therefore, a breach and flow initially impacts only one side of the vessel. Since the LNG flow volume is spread across a large number of compartments within the double hulls, the time required to flow into and fill these compartments is slightly longer than observed for the Moss ship designs. As with the Moss ships, LNG also flows out of the vessel forming an LNG pool external to the ship.

The flow analyses conducted for this study showed that for the larger breach events, as much of 40 percent of the LNG will likely flow into the LNG ship. The spill and flow analyses showed that the internal flow of the LNG in a Moss ship will be completed within ten and fifteen minutes, at which time the LNG will all flow out onto the water. For a Membrane ship, LNG flow into the ship will be completed in about 10 minutes, and then the LNG will flow out onto the water. The results for the external flow analyses show that for the various breach events and ship designs, pool diameters of between 180 m to 350 m for the Moss, and between 200 m to 330 m for the Membrane LNG ships are generally expected for the larger breach events of one tank (Figueroa et al., 2011).

The flow modeling analyses were used to directly support the cryogenic and fire damage and hazard modeling. The results from the internal flow analyses were used to identify the regions and timing of cryogenic LNG flow and damage within the ship structures, and the results from the external flow analyses were used to identify the diameters of the LNG pools outside the vessels for each breach and spill event and used in subsequent fire modeling to identify regions of the vessels affected and damaged by the pool fires.
LNG SHIP STRUCTURAL STEEL CRYOGENIC AND FIRE DAMAGE TESTING AND MODELING HIGHLIGHTS

While the previous section described the LNG flow analysis, a series of material tests, large-scale fracture tests, and pool fire modeling were conducted to model and assess the response and damage of the LNG vessel’s steel structure to both cryogenic LNG flow during a spill and large fires. The results developed were used to establish damage levels to the LNG ship for different breach and spill sizes, and therefore provide insight into what type of risk mitigation and management options are needed to address the major drivers, and what approaches might be the most effective. Therefore, in this section we provide some background information on the results of the cryogenic and fire damage testing and modeling as it relates to understanding risk mitigation and risk management challenges, and what options would be most useful or appropriate to reduce major ship damage and related hazards.

It is well known that ship structural steels are susceptible to both low temperature brittle fracturing from cryogenic LNG spills and high temperature material softening during extended contact with a fire. Figure 4 shows an example of cryogenic fracturing of LNG ship steel deck plates from a relatively small LNG spill.

![Figure 4. Example of Cryogenic Damage of Steel Ship Decks from LNG Spills](image)

In order to predict the thermal (both cryogenic and high temperature) structural cascading damage response of the ships, testing was required on ship structural steel materials to determine the material behavior at extreme temperatures (from -161°C for cryogenic LNG temperatures and up to 1000°C for LNG fire temperatures). Therefore, a series of material property and material failure tests were performed on two ABS steels that are representative of the structural steels used in standard LNG ship construction. The testing of these two materials enabled a bounding of the response of the range of steels found in LNG ships (Kalan et al., 2011, and Petti et al., 2011).

The results of the cryogenic and high temperature testing of the mechanical and structural properties of the ship steels identified the following damage and risk concerns:

- The fracture toughness of typical ship steels decreases dramatically at temperatures below -50°C
- Brittle fracture is likely of typical ship steels at temperatures below -120°C from inherent steel and construction flaws
- At 500°C, typical ship steels are only about 50% of maximum strength
- At 600°C, typical ship steels are only about 25% of maximum strength
- At 800°C, typical ship steels are only about 10% of maximum strength
The basic material tests provided initial estimates needed for developing and validating a ship steel damage model. However, a series of large-scale fracture tests (Kalan and Petti, 2011) were required to further calibrate and then validate the damage model needed for modeling the full vessel behavior. The assessment of the ships was accomplished through a series of computational finite element analysis of models of each LNG ship.

Cryogenic testing of typical steels lead to an estimation of lower and upper bound heat transfer coefficients of 400 and 1080 W/m²-K. Numerical modeling of ship structures showed that regions identified from the flow analysis that come into contact with the spilled LNG will reduce in temperature from 20°C to -148°C in from 5 to 10 minutes. Analyses showed that this holds for steels both above and below the waterline for most conditions. These testing and modeling results highlight the relatively fast cool down of the ship steels that can occur when they come into contact with LNG.

Test data on representative ship structures also showed that cryogenic temperatures remained localized to the areas contacted by LNG. These two sets of results suggest cryogenic damage can happen quickly during spills, and that minimizing the areas coming into contact with LNG is a major way to limit or mitigate the potential for cryogenic ship damage.

Fire analyses using FUEGO, a massively parallel computational fluid dynamics (CFD) fire analysis code developed and used by Sandia, were conducted to help identify the regions of the ships affected by an external LNG pool fire. FUEGO was used to conduct all fire-structure interaction modeling aspects of the fire analysis. The primary use of FUEGO was to estimate the envelope of the fire over the vessel for a range of wind and environmental conditions. In many wind scenarios, the fire impact extends beyond the diameter of the pool along the length of the vessel due to radiation and the wind makes the fires lay over onto the ships. This increases the areas impacted by heating from the fire, which includes the sides and the tops of the LNG ships.

Similar to the method used to establish the cooling rates, a combination of testing and analysis were used to determine the heating rates of the ship hulls as inputs to the structural thermal damage model. In this case, a half-symmetry model representative of the outer and inner ship hulls was created in the finite element code MSC PATRAN/Thermal. Based on the data from the large LNG pool fire experiments (Blanchat et al., 2010) and insulation testing (Blanchat, 2011), a surface emissive power of ~290 kW/m² was used to estimate the heating rate on the outer hull, which in turn heated the inner hull by radiation heat transfer. The heating was applied to the fire impacted regions of the LNG ships as determined from the fire modeling analyses from FUEGO for an LNG pool fire. The purpose of the simulation was to obtain information on representative maximum temperature responses of the inner and outer hull of an LNG ship exposed to a large LNG pool fire. A fixed “water” temperature was assumed below the waterline on the exterior surface of the outer hull.

The applied heating remained relatively localized to the region where it was applied even after 30 minutes of heating simulation, which was similar to the localized response observed in the cooling rate testing and simulations. From the fire thermal analyses, the temperature of the outer hull is expected to reach approximately 1000°C, while the inner hull could reach approximately 775°C within approximately 15 minutes. Based on the flow of LNG and the size of pool, the fires are expected to last between 20 and 40 minutes. This analysis compares favorably with heating results measured on inner and outer hulls on large-scale ship structure-insulation fire damage tests conducted as part of this cascading damage study (Blanchat, 2011). When compared to the ship steel strength data shown above for these temperatures, significant deformation and damage of the ship structure that would be in contact with a long-term fire could be significant. This suggests that approaches that could reduce or mitigate fires sizes or fire temperatures to the ships structures would be extremely beneficial.
LNG SHIP DAMAGE ANALYSIS SUMMARY

The LNG ship structural damage analyses and assessments employ finite element models, the material properties measured and cryogenic damage models developed, the cooling and heating rates measured, and the timing of the cooled and heated regions from the LNG flow and fire analyses to develop estimates of the timing and extent of damage of both LNG ships. From the spill and flow analyses conducted, the large to very large breach events give very similar overall LNG flow within the ship structures, with the major difference being some minor variation in the timing of the cooling of different regions. For this reason, a single detailed structural damage analysis was performed for each type of LNG ship.

For the Moss and Membrane ships, the regions exposed to LNG flow were analyzed for cryogenic induced fracture. The LNG flow results were used to develop a series of regions of structural steel cooling that changed as the LNG flowed into the internal structure of the ship. The temperature and damage states within the ships were correlated with the LNG flow and cooling rate information. As discussed, no difference in cooling rate was assumed for the regions of the ship’s outer hull above or below the waterline. The flow analysis showed widespread LNG contact with steel plate surfaces within 30 seconds. Based on the extent of the flow and the cooling rates data developed, the temperatures of the elements were decreased from 20°C to -148°C over 10 minutes. The different regions had their temperature decreased by the same temperature range and time, but the start of the cooling was delayed as required to simulate the timing of the flow of LNG within the space surrounding the cargo tank for up to a cooling time of approximately 14 minutes.

As mentioned, the large to very large breach events provide generally similar LNG flows for both ships that were therefore similar in the extent of the cooling regions. The most significant differences were based on breach location, which alters the timing of the structural cooling and the eventual amount of LNG flow into the ship versus outside the ship. In some credible breach events, significant water entrainment can occur within approximately 5 minutes. This could have several consequences. One plausible result could include the water displacing the LNG at the lower regions of the vessel below the waterline due to the higher density of water. This could minimize cooling and reduce potential structural damage. However, the mixing of LNG and warm seawater will cause a rapid vaporization of the LNG with potential pressurization, both of which could cause additional ship structural damage. These issues were considered in developing Moss and Membrane LNG ship damage conclusions.

For both ships, based on the cryogenic structural damage analysis, much of the inner hull near a large breach event was damaged, reducing the ability of the vessel to resist hydrostatic loads from the surrounding seawater. In addition, the ship structural moments of inertia, or section modulus (the parameter that defines the ship’s capability to resist bending loads and deformations) was drastically reduced, which impacts the ability of the ships to remain stable and afloat in the water.

From the fire analysis, much of the ship structures near the fire on both the side and top of the ship could reach temperatures between 775°C and 1000°C for the inner and outer hulls. At these temperatures the material properties of ship structural steels were shown from our testing to be severely weakened, having less than 10 percent of their original strength, and to deform significantly. Based on the cryogenic damage and weakening of the material exposed to the fire, the reduced plastic bending moment capacity for the Moss and Membrane ships as a general function of time was developed as shown in Figure 5. The plastic bending moment capacity is defined as the bending moment that would lead to the entire cross-section of the ship yielding and creating essentially a plastic “hinge.” The evaluation of the plastic bending moment capacity is often used in many extreme event risk analyses to more accurately predict the likelihood of overall structural system damage or failure during extreme events.
The moments were normalized by the full undamaged plastic moment capacity of each ship cross-section. The cryogenic damage causes an approximate 30% reduction within 5 to 10 minutes depending on the ship design, with the fire causes an additional 40% to 50% reduction between 20 and 30 minutes depending on the ship design. However, the reduction in the plastic bending moment capacity does not fully address the concern with overall damage. The capacity estimates assume that the cross-section is in a condition to obtain the full strength of the materials without section buckling. The sections of the inner and outer hull at the top of the ship are affected by the fire and have little resistance to tension. Therefore, the ship was judged to have essentially little remaining strength and to be overall disabled and severely damaged.

From the testing results on cargo tank insulation damage during a fire, it was determined that damage of additional cargo tanks from a fire would occur well after 40 minutes (Blanchat, 2011). This would suggest that any additional release of LNG from damage from the initial spill would not occur simultaneously, and therefore not increase the size or hazard distances from a fire, but might occur sequentially, which could increase the duration of a potential fire.

For the small breach events noted in Table 1, which could occur from a number of credible intentional events, the spill rates will be more than a factor of 1000 times less than that of the large breach events considered. This puts the associated smaller spills into a regime that would typically fall within current spill detection and safety systems on Moss and Membrane LNG ships. The large reduction in spill rates, cryogenic damage and fire damage potential suggests that Moss and Membrane LNG ships that would experience small breach events would have sufficient time to find an appropriate anchorage location and work with the local public safety agencies and the Coast Guard to determine appropriate damage assessment, safety, and possibly repair procedures.

The medium size breach sizes noted in Table 1, 0.5 m² (2.3 feet square) because of the physics of the flow conditions, will reduce the LNG flow rate into an LNG ship by a factor of approximately six, relative to a large LNG spill. As such, the full cryogenic cooling and damage of all the compartments between the LNG hulls for each ship could take as much as six times as long. But based on the flow analysis conducted for the medium holes, the LNG flow internal to the ship reaches the keels of the LNG ships only a few minutes later than the larger spills. This suggests that for the medium size breach events and spills, the full cryogenic damage could take from 10 minutes to 60 minutes longer than for the larger spills. Unfortunately, the fire damage will
still occur over the original time period calculated, and therefore the overall structural damage might not change significantly. Therefore, a medium size breach event could double or triple the time before an LNG ship becomes disabled, but it would still occur in within a few hours or so of the breach event and spill, which might not provide significant time to move the LNG ship to a safe anchorage.

The significant findings and conclusions from the LNG ship cascading damage analyses are summarized below.

Summary Results for Small Breaches

- For the small breach events, which could occur from a number of credible intentional events, the spill rates will be more than a 1000 times less than that of the large breach events considered.
- This puts the associated smaller spills into a regime that would typically fall within current spill detection and safety systems on Moss and Membrane LNG ships.
- The Moss and Membrane LNG ships would have sufficient time to find an appropriate anchorage location and work with the local public safety agencies and the Coast Guard to determine appropriate damage assessment, safety, and repair options.

Summary Results for Medium Breaches

- Similar results as the large and very large breaches, just over a slightly longer time period (approximately 1 – 2 hours).
- The Moss and Membrane LNG ships would not likely have sufficient time to find an appropriate anchorage location prior to becoming disabled of severely damaged.

Summary Results for Large and Very Large Breaches

- The structural integrity can be severely compromised for large spills with significant sections of the hull cracked and no longer capable of effectively resisting any loads.
- Both ships were judged to be disabled and severely damaged due to a large cargo tank breach and spill.
- Neither ship would be capable of movement and would need to have any remaining LNG cargo transferred.
- Simultaneous multi-cargo tank cascading damage spill scenarios are judged to be unlikely, though sequential tank spills are possible. These sequential spills are not expected to increase the hazard distances, but could increase the duration of the fire.

From an LNG vessel damage viewpoint, the cascading damage analyses conducted by Sandia that were presented above suggest that significant damage is likely to LNG vessels from medium and large breach events and spills. Therefore, a large breach and spill could have both short-term and long-term impacts on public safety, energy security and reliability, and harbor and waterway commerce as well. For this reason, significantly more attention and proactive measures should be considered and taken to prevent the possibility of larger breach and spill events or to try and mitigate the cryogenic and fire impacts on ships structures for the larger LNG spills.

DISCUSSION OF RISK MITIGATION AND MANAGEMENT OPTIONS AVAILABLE TO REDUCE SPILLS

As noted in both the 2004 and 2008 Sandia LNG reports, risk prevention and mitigation techniques can be important tools in reducing both the potential for a spill and the hazards from a spill, especially in locations where the potential impact on public safety and property can be high. However, what might be applicable for cost-effective risk reduction in one location might not be appropriate at another location. Therefore, coordination of risk prevention and management approaches with local and regional emergency response and public safety officials is important in providing a comprehensive, efficient, and cost-effective approach to protect the public and property at a given LNG import or export location.
Hazard and risk management options focus on approaches that can be used to actively prevent or mitigate larger spills, since these events are the ones that are less common, but have the highest consequences. In looking at risk mitigation and management options, the technical review group identified three major categories to focus on. Options for each category are highlighted in tables below and discussed. The major categories identified include:

- Options to help reduce the possibility of spills, especially large spills,
- Options to reduce ship damage if a large spill did occur, and
- Ship design modifications that could help protect the ship from damage and the crew from danger from a large spill and fire.

### Potential Risk Mitigation Measures to Reduce the Likelihood of a Large Spill

<table>
<thead>
<tr>
<th>Potential Risk Management Approaches to Reduce the Likelihood of Large Spills</th>
<th>Rationale</th>
<th>General Issues</th>
</tr>
</thead>
<tbody>
<tr>
<td>Improve control of other vessel transits and movements during marine LNG transit or while at berth</td>
<td>LNG ships are designed to handle low speed impacts, making sure speeds of big vessels are slow minimizes any potential damage</td>
<td>In large ports, passing traffic might not be able to be stopped, but as long as the other traffic is “cleared” and is end on or nearly end on for large ships it should be OK. Control of other vessel transits and movements during the LNG ship transit period and while at berth could minimize accidental or intentional events</td>
</tr>
<tr>
<td>Evaluate options to improve LNG tanker escorts and improve protection from potential large intentional breach events through enhanced standoff, or active interdiction</td>
<td>Information suggests large spills are more likely from intentional events, therefore need ways to prevent from getting close to an LNG ship</td>
<td>A review of the suitability of LNG carrier escorts could highlight escort requirements needed to prevent large intentional events. This could include more escort boats, active interdiction capabilities, etc.</td>
</tr>
<tr>
<td>Evaluate options to improve offshore LNG operations to improve protection from potential large breach events through active interdiction, monitoring, or enhanced standoff technologies</td>
<td>Deepwater Ports have greatest chance for large intentional events due to potential large ships at high speed and less surveillance</td>
<td>Offshore support vessels for Deepwater Ports may need a higher level to security and interdiction capability to minimize large offshore threats. Port authorities and LNG ships could need additional operational awareness and monitoring to react more quickly to intentional or accidental events. Assess and consider other passive and active protection and interdiction options.</td>
</tr>
<tr>
<td>Provide enhanced standoff systems and protection for LNG ships</td>
<td>Increased standoff of only several meters can significantly reduce breach sizes, spills, and hazards</td>
<td>Standoff systems can be active or passive. But in all cases, solutions have to be weighed against any impacts the approach would have on ship and crew safety.</td>
</tr>
<tr>
<td>• During transit near populated areas as appropriate</td>
<td></td>
<td>Could be harder to control passive systems during transit operations.</td>
</tr>
<tr>
<td>• While at LNG terminals during LNG discharge or receiving operations</td>
<td></td>
<td>Both passive and active systems might be more easily integrated into terminal security capabilities.</td>
</tr>
<tr>
<td>• Deployable anti motor-boat booms</td>
<td></td>
<td>Deploying or removing a boom currently takes up to 2-3 hours. This is a potential safety concern as the ship might have difficulty moving in an emergency situation unless quick disconnect approaches are used.</td>
</tr>
</tbody>
</table>
Accidental Events – The LNG shipping industry has an exemplary safety record. Since commercial LNG operations began in 1964, over 66000 loaded voyages have been completed, transporting over 6 billion m$^3$ of LNG. During this period there have been only 3 significant groundings, none of which resulted in loss of LNG and there have been no serious collisions involving an LNG carrier. This is attributable to a very high standard of equipment design such as the double hull designs, good operational practices, and safety training.

From 1999 to 2010, the volume of LNG shipped per year doubled, and the number of LNG ships in service increased more than 3 fold. Therefore, where not already undertaken on a regular basis, operational procedures should be reviewed to ensure that increased port traffic or LNG shipments have not increased the likelihood or risk of serious damage to an LNG carrier. This is most important where there is a possibility of a large displacement vessel colliding with an LNG carrier at a speed and angle of incidence that may result in penetration of the cargo containment system. Risk can be reduced by measures such as; control of movement of other large vessels while an LNG carrier is transiting the port or berth, escort towage of large vessels when passing an LNG carrier at berth or terminal, and moving safety zones enforced around an LNG carrier while it is in transit.

Evaluations have shown that the largest accidental breach sizes and spills will occur with collisions with larger ships at higher speeds. Therefore speed control in port areas is a very effective control approach for large and small ships. The control and speed management of larger ships at deepwater or offshore ports is more problematic, but the impact of large spills on the public are much reduced at these port locations.

Intentional Events – When in the port area there is little the crew of the LNG carrier can do to mitigate the probability of an intentional event, other than those actions approved and required under The International Code for the Security of Ships and Port facilities (The ISPS Code). Therefore, the prime responsibility for protection against intentional events will have to come from the port authority, terminal operator, and local LNG ship escort and protection services. Integration and communication between responsible protection agencies and services is an area of risk mitigation by ensuring all communications and activities are well planned and closely coordinated.

An area of protection that should be considered is a review of LNG ship escort protection. Improved enforcement of exclusion zones around the ship in transit and while at berth at the terminal provides more time to interdict or stop many intentional events, especially those that would be similar to a water-borne attack like the USS Cole. Enhanced security services can be considered at all operations, but would be most important to consider where hazards to the public, property, or shipping warrant it. Passive protection measures that increase standoff distances between the intentional event and the LNG ship, such as large fenders or booms that are used at many naval installations could be considered. But it has been identified that these types of systems would need to be designed to allow the ship to depart from a berth or terminal quickly in case of an emergency.
POTENTIAL RISK MANAGEMENT APPROACHES TO REDUCE SHIP DAMAGE AND PUBLIC HAZARDS

It was generally agreed by the technical review panel and LNG shipping industry participants that the most effective way to reduce risk to the public during LNG transport was by prevention of an incident, accidental or intentional, as described above. The data and results from the cascading damage study suggest that once a large scale breach, spill, and fire has started, it will be impossible prevent some level of cryogenic damage to the ship structure or to extinguish the fire. For large spills, the LNG ship will experience some level of structural damage.

Terminal and port contingency plans should be reviewed to ensure that they adequately cover the consequences of an accidental or intentional event. This should include actions required of the vessel, terminal, port authority and the population in the area adjacent to the terminal, as well as local and regional emergency services, to prevent or reduce the number of injuries and property damage.

If a breach of the containment system and subsequent fire occurs while the vessel is in transit, the vessel should ideally be anchored or grounded. With the LNG ship in a fixed position and not drifting out of control, emergency planning will be aided; however given the possibility that the size and intensity of the fire may develop very rapidly how the crew may be able to react is uncertain and preplanning will be important for the crew and public safety.
In case of a large spill and fire, a large LNG ship will need to quickly move out of the main channel to prevent the long-term blockage of the channel. Therefore, appropriate grounding locations and procedures need to be in place to prevent inappropriate grounding of an LNG ship on fire. Local planning regulations should be examined to ensure unsuitable development is not allowed close to the terminal or potential grounding locations. This would include schools, hospitals, residences, etc. In the UK and European countries this is mandatory, as is regular updating of contingency plans. With a badly damaged and unseaworthy LNG ship that has likely been grounded, either intentionally or accidentally after a large spill and fire, there will be a need to lighter the remaining LNG in the ship for safety reasons. This could be done by venting the

<table>
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<tr>
<th>Potential Options</th>
<th>Rationale</th>
<th>General Comments</th>
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<tbody>
<tr>
<td>Review emergency response coordination and procedures to</td>
<td>Need to pre-plan where ship can be moved to be out of ship channel so safety</td>
<td>Make sure contingency plans for port and LNG ships have procedures that adequately cover the consequences of a significant accidental or intentional event. This should cover the vessel moving to a safe anchorage or grounding to monitor, inspect and assess damage and needs including lighter.</td>
</tr>
<tr>
<td>consider LNG ship maneuvering to safe anchorages to monitor, inspect, and</td>
<td>assessment can be done without impacting port traffic</td>
<td></td>
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<tr>
<td>assess ship damage, stability, seaworthiness, and long-term safety issues.</td>
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</tr>
<tr>
<td>Consider use of water in ship ballast tanks to reduce cryogenic spill damage</td>
<td>Even some water in ballast tank could reduce cryogenic damage in the critical</td>
<td>Effectiveness depends on how much ballast can be carried and the amount of structure that can be protected. Likely will require cargo tanks to be 5% or more empty in many ports because of the shallow channels. Therefore this option will be port, ship, and LNG cargo specific. Has an economic impact to LNG operators, and will need site-specific evaluation.</td>
</tr>
<tr>
<td>while in port areas when loaded.</td>
<td>outer hull area to improve ship survivability</td>
<td></td>
</tr>
<tr>
<td>Utilization of high performance fire fighting tugs with 7000 m³ to 11000 m³ per</td>
<td>The tugs that are used to assist an LNG ship in port are built for their</td>
<td>The tugs that are used to assist an LNG ship in port are built for their maneuverability. Tugs with this large fire fighting capability may have to be dedicated for firefighting because they are not very maneuverable. Assessment needed to see if special firefighting tug is feasible in port areas and can get around port to get close enough to cool down the LNG ship decks, weather covers, etc. and still survive a fire.</td>
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<tr>
<td>hour (30,000 – 50,000 gallons per minute) fire monitor capacity to spray down</td>
<td>maneuverability. Tugs with this large fire fighting capability may have to</td>
<td></td>
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<tr>
<td>ship hulls to reduce the thermal damage from a fire</td>
<td>be dedicated for firefighting because they are not very maneuverable.</td>
<td></td>
</tr>
<tr>
<td>Remote controlled high capacity water monitors on jetty or terminal capable</td>
<td>Terminal-based water monitors could be effective for both LNG ship and</td>
<td>Terminal based water monitors that are remote controlled could reduce thermal impact on ship from a fire while at berth. Could protect ship and terminal from structural damage. Does not address spill and fire while ship is in transit, but might be part of a combined solution.</td>
</tr>
<tr>
<td>projecting water onto and across vessel</td>
<td>terminal safety</td>
<td></td>
</tr>
<tr>
<td>Establish lightering procedures and capabilities for marine LNG imports for</td>
<td>Addresses safety issues of how to move cargo from a damaged ship</td>
<td>This will be weather and site specific. Requires available hoses, equipment etc, to be available at the terminal, port, or on the LNG ship. But lightering will be a very likely requirement and a safe approach developed.</td>
</tr>
<tr>
<td>near-shore terminals and operations, as appropriate</td>
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</tbody>
</table>
remaining cargo, if appropriate, or transferring the remaining cargo to another ship or barge. Venting might be easy, but may have safety concerns. Lightering therefore may be a complex requirement that needs to be planned and the equipment pre-provisioned well in advance of a large spill. This is not a simple process and needs to be thought through fully, and will have significant safety benefits to the public if done well.

Two other ideas proposed were to look at using the ship ballast tanks and partially fill them with water to reduce the impacts of the cryogenic LNG on the lower portion of the ship inner and outer hulls, and to use high performance firefighting equipment, such as Level 3 fire fighting tugs. These risk mitigation concepts could help reduce the damage to the ship hulls from both the cryogenic fracture and fire thermal softening. Putting water into the ballast tanks could have some limitations, namely the draft of the ships could be increased to a point that they might be able to transit shallower ports. This can be balanced by reducing the amount of LNG cargo carried. Therefore this approach will have economic impacts to the LNG shipping companies and therefore will likely required tradeoffs between LNG cargos and site and ship specific draft limitations, LNG ship stability, and structural capability.

The use of high performance fire fighting tugs (FiFi3) fitted with high capacity monitors to spray water onto the ship hull to help reduce the thermal damage to the ship’s structure was discussed. FiFi3 tugs have 4 monitors with a range of 150m and a height of 70m, the total capacity of which is 9600 m$^3$/hr; they are also provided with a deluge system. But these tugs are large and are not suitable for use for maneuvering and berthing large LNG ships and therefore would be a dedicated, single use, fire fighting tug. Depending on the port and number of LNG shipments, this might not be cost effective. Also the port needs to be of a size that a large fire fighting tug could maneuver to get close enough to the LNG vessel to adequately cool the LNG vessel hulls to minimize ship damage.

Another suggestion was the installation of high-capacity water monitors, similar to those on FiFi 3 tugs, could be installed at the terminal at the transfer jetty. This would provide some protection for terminal jetty staff and ship’s crew trying to escape, but would also reduce thermal damage to the terminal and ships structure, which would aid post event removal of the vessel. Large volumes of water may also prevent possible escalation of the fire to shore facilities, which could subsequently pose a further risk to the public. Water monitors supplied from the terminal would be more reliable source of coolant than that supplied from the current ship deluge systems, which only cover the top of cargo tanks, or of smaller fire fighting tugs. The one drawback is that this approach would not provide ship cooling capability while the LNG ship is in transit to or from a terminal.

While not related to public protection, other measures suggested may be beneficial in reducing risk to the ship, the terminal, and the terminal and ship staff and crews that will aid in the recovery of the ship after a large spill and fire. Because of the size of the fires from a potential large spill, operational contingency plans for the protection of staff and crew should be reviewed and include measures such as temporary refuge arrangements for personnel and crew protection.
SAFETY MODIFICATIONS FOR LNG SHIPS

The technical advisory group also considered potential structural changes to LNG ships that could have significant benefits to LNG ship survivability in case of a large spill and fire. Each of these changes would have to be considered from a ship structural and seaworthiness standpoint and may not be simple retrofits. But the review panel thought that as more ships are being constructed, that some recommendations on safety elements to consider for future ship designs, or some minor modifications that can be included the next time the current ships are in dry dock, will provide shipping companies and ship owners with some realistic safety measures to evaluate and consider.

There are many lightweight fire resistant materials and paints on the market that might provide enhanced thermal protection for LNG ship outer hulls. These paints and materials would have to be evaluated for sea conditions and impacts on ship stability, corrosion, life expectancy, etc., but should be investigated as a reasonable consideration to help prevent thermal damage to the ship hulls from a large fire.

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<tr>
<td>Add lightweight fire insulation on cargo tanks covers, or fire retardant paint on ship structures</td>
<td>Could protect cargo tanks or ship structural steel from thermal impacts of spills and fires</td>
<td>Ship coatings are notorious for hiding corrosion, though there have been advances in materials, coatings, and paints claiming fire resistance. Testing and evaluation will be needed. Impacts on ship stability will need to be evaluated.</td>
</tr>
<tr>
<td>Modification of ship deluge systems to improve full coverage of cargo tanks and other areas such as lifeboat areas and crew muster areas</td>
<td>Improve thermal resistance of cargo areas and top deck and improve ability of crew to survive large fires</td>
<td>Major ship modification to approve and include into a revised IGC code.</td>
</tr>
<tr>
<td>Reduce connectivity of void spaces or provide hatches to reduce connectivity of void spaces</td>
<td>Reduce ability of LNG to flow to various locations inside the LNG during a spill</td>
<td>Retrofits could be problematic, feasible likely only for new ship construction. Impacts on operations and safety need to be evaluated.</td>
</tr>
<tr>
<td>Provide alternate escape locations for crew with water spray protection, either from ship or from terminal</td>
<td>Enhances crew survivability</td>
<td>Requires ship and terminal modifications.</td>
</tr>
<tr>
<td>Provision escape sets for methane as proposed in revisions of IGC code</td>
<td>Large spills and fires could deplete oxygen plus high levels of combustion products such as carbon monoxide</td>
<td>Already being considered as part of IGC for other cargos</td>
</tr>
<tr>
<td>Additional diesel/hydraulic deluge pump in foc'sle space</td>
<td>Provides more deluge capacity for cargo tank, top deck, and crew escape</td>
<td>Better protect ship and crew in large spill and fire scenario</td>
</tr>
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</table>

LNG ships have deluge systems that cover only the very top of the cargo tanks. Significantly increasing the overall deluge system design and capacity could provide significant protection for the ship and crew in the case of a large spill and fire. The complexity of doing that easily to provide the appropriate level of deluge water flow and the power requirements for such flow to appropriately protect the ship hulls would have to be fully evaluated, but with an existing infrastructure in place, this might be a good opportunity to consider.
To help prevent the flow of LNG between the hulls during a large spill, consideration of ways to reduce the connectivity of void spaces could be considered. As the cryogenic testing and flow modeling and analysis showed, the regions of the ship structural steel that were damaged were only those areas that came into direct contact with the spilled LNG. Reducing the connectivity of those spaces between the hulls could prevent the LNG from flowing into all areas and therefore protect major regions of the ship from brittle fracture and reduce overall ship damage, stability, seaworthiness, etc. While it might be impossible to do this totally for safety and inspection reasons, it might be possible to rework penetration configurations and hatch designs that have the flexibility to be used to close off some connected passages while transiting major port areas or areas where the impact to the public from a damaged ship could be significant.

The size and intensity of fires from large LNG spills suggests that additional consideration of the safety of the crew should be considered. Opportunities to enable them to safely escape during a large fire will benefit operations to salvage and lighter the ship after the fire. Having a safe crew that is available to help after the fire would significantly improve emergency response efforts in stabilizing the ship and its systems and increasing public and port safety after the large spill and fire.

CONCLUSIONS

With the focus on public safety, effective risk mitigation measures must clearly be linked to those that relate to public protection and ship recovery operations:

1. Prevention measures through improvements in traffic and people movement control should be reviewed to try and prevent a large spill from happening.

2. Since the potentially resulting fire cannot realistically be extinguished due to its intensity and short duration, review near-by community emergency response to a significant incident as described in the report.

3. In addition to the above, measures have been suggested related to the protection of the ship and terminal staff and ship crew. While not related directly to public protection, ship and terminal operational contingency plans and improvements will reduce the risk to staff and crew that could support recovery of the vessel post incident and mitigate long-term public safety issues with the ship after a fire.

As noted in both the 2004 and 2008 Sandia LNG reports, risk prevention and mitigation techniques can be important tools in reducing both the potential for a spill and the hazards from a spill, especially in locations where the potential impact on public safety and property can be high. However, what might be applicable for cost-effective risk reduction in one location might not be appropriate at another location. Therefore, coordination of risk prevention and management approaches with local and regional emergency response and public safety officials is important in providing a comprehensive, efficient, and cost-effective approach to protect the public and property at a given LNG import or export location.

From an LNG ship damage viewpoint, the analyses conducted and presented in this report suggest that significant damage is likely to LNG ships from medium and large breach events and spills. Therefore, a large breach and spill could have both short-term and long-term impacts on public safety, marine import energy reliability, and harbor and waterway commerce at some sites. For this reason, significantly more attention and proactive measures should be considered for preventing the possibility of the larger breach and spill events, or for mitigating the cryogenic and fire impacts of larger spills on LNG ships.

The hazard risk management options should be focused on approaches that can be used to actively prevent or mitigate larger spills. Some risk management approaches that were suggested by the members of the Technical Review Panel that should be considered to help reduce the possibility of the event or hazards to the ship and the public include:
• Control of other vessel transits and movements during LNG ship transits and operations,
• Review LNG ship escorts operations to improve the ability to enforce exclusion zones through enhanced standoff and active interdiction approaches,
• Review offshore LNG operation security measures to help improve the ability to enforce exclusion zones through active interdiction or enhanced standoff approaches,
• Review and consider the benefits of using high performance fire fighting water monitors to improve fire protection to the LNG ship, terminals, and ship personnel from a large LNG fire,
• Improve emergency response coordination and procedures for the LNG ship, terminal or port, port authority, and emergency response groups to reduce the overall impacts and consequences of larger spills,
• Review contingency plans for the port and LNG ships to ensure procedures are in place to address larger spills, covering options for moving the ship to a safe anchorage to monitor, inspect, and assess damage and long-term response options including lightering, and
• Review standard LNG ship safety and security operations and equipment that could be improved or modified to reduce LNG ship and cargo tank damage and hazards during a large spill and better protect the ship crew so that they can help accelerate the post fire recovery.

REFERENCES


